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OPTICAL EQUALIZATION WITH BEAM COUNTER-

PROPAGATION

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OPTICAL EQUALIZATION WITH
BEAM COUNTER-PROPOGATION

RELATED PATENT APPLICATIONS

5   This application depends and claims priority from U.S. Provisional

Patent Application No. 60/269,521, filed 2/16/2001, U.S. Provisional Patent

Application No. 60/269,753, filed 2/16/2001, and U.S. Provisional Patent

Application No. 60/276,817, filed 3/16/2001, which are hereby incorporated by

reference herein. This application is further related to commonly owned U.S.

10   patent application Ser. No. _____ [24133711.20], filed concurrently

herewith, which is also hereby incorporated by reference herein.

TECHNICAL FIELD

The present application relates to optical communications, and, more

particularly, to devices and methods for achieving optical equalization.

15   ## BACKGROUND

As telecommunications bandwidth requirements continue to rise, electrical

wires as a communication medium are pushed to their capacity. The limitations

of electrical wires has resulted in a growing trend towards the use of optical

fibers to facilitate voice and data communications.

Communication signals traversing a communication channel lose strength as the distance traveled increases. To increase the distance that the signal travels, the signal is regenerated at certain points along the communication channel. Electrical signals are often regenerated using repeaters. In contrast, optical signals are regenerated using optical amplifiers.

A common optical amplifier is known as an Erbium Doped Fiber Amplifier (EDFA). An EDFA comprises a section of fiber, which is doped with erbium. A high-powered beam of light is mixed with the input signal using a wavelength selective coupler. The mixed light is guided into the erbium-doped section of fiber. The high powered light beam excites the erbium ions to a higher state. The photons of the signal light receive energy from the erbium ions when the erbium ions return to a lower state, thereby amplifying the signal.

The gain of the output signal from an optical amplifier often varies with signal wavelength. For example, an optical amplifier such as a Raman amplifier may produce a higher gain in lower wavelengths and a lower gain in higher wavelengths. In theory, other another type of amplifier might produce a higher gain in higher wavelengths and lower gain in lower wavelengths. The gain produced by such amplifiers is known as "titled gain." In other cases, the optical amplifier may produce a gain that varies more complexly with respect to the wavelength.

SUMMARY

Disclosed herein are equalization methods and devices which can process an incoming optical signal or optical beam to compensate for wavelength-dependent variations in the gain or transfer function of amplifiers or other optical elements which come prior to the equalization devices in an optical signal path. The equalizer processes the incoming signal by imparting wavelength-dependent filtering or gain upon the incoming optical signal, thus compensating for the generally undesirable wavelength-dependent transmission functions of other components in the optical signal path.

In many instances, the target or desired power spectrum at the output of the optical equalizer will be flat. In other cases, it may be desirable to have a gain profile which is slanted linearly, either increasing or decreasing, with wavelength, and in still other cases a more complex gain profile may be desired.

In one technique, a control algorithm compares the power spectrum from the equalizer and compares that actual power spectrum to the target power spectrum. The actual spectrum can be subtracted from the target spectrum, to yield a difference or "delta" power spectrum, which will represent the change that is needed to be made to the equalizer in order to achieve the target power

spectrum at the equalizer output. In an equalizer having multiple stages, the delta power spectrum can be broken down into component values corresponding to harmonic components of the delta power spectrum, and these component values can in turn be applied to individual filter stages within a

5   multiple-stage equalizer so the equalizer can more nearly achieve the target power spectrum.

In another technique, a target transfer function is determined based on the spectral energy of the amplified signal. The actual transfer function of the equalizer is then measured, and the measured transfer function and the target

10   equalization function are compared. A difference between the measured target equalization function and the actual transfer function can be calculated as described above, and based on the calculated difference between the measured target equalization function and the actual transfer function. This difference between the target transfer function and the actual transfer function of the

15   equalizer should yield approximately the same delta power spectrum as was calculated using the previous technique. Again, the delta power spectrum can then be broken down into component values corresponding to harmonic components of the delta power spectrum, and these component values can also be applied to the multiple filter stages of a multiple-stage equalizer.

20   In another technique, based on the harmonic component values of the delta power spectrum, a series of phase constants and amplitude constants are

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calculated. Based on these calculated phase constants and amplitude constants, the control voltages applied to at least one of a plurality of harmonic filters are adjusted. These adjustments could be made according to a calculation which has been defined in the control algorithm, or a look-up table could be provided

5   in memory correlating certain phase constants and amplitude constants to control voltages to the filter stages.

Additionally presented herein are architectures, that improve performance of optical devices in achieving equalization. One architecture includes a beam displacer or separating element and a component assembly. The incoming

10   amplified signal is received by the beam displacer and split into two beams. The two beams are counter-propagated through the component assembly in opposite directions, but through substantially the same spatial path. Propagation along the same spatial path reduces the effect of spatially varying optical properties within optical components and improves the performance of

15   the equalizers and the quality of the equalized signal.

Another architecture includes a beam displacer or separating element and a component assembly. The incoming amplified signal is received by the beam displacer and split into two beams. The two beams are counter-propagated through the component assembly in opposite directions, but through

20   substantially the same spatial path. The beams are then received by a redirecting element, which redirects the two beams to a beam displacer. The

beam displacer, acting in this context as a beam combiner, combines the beams, resulting in an output signal which may be equalized, or have a substantially flat power spectrum, or may have a more complexly varying power spectrum allowing it to pre-compensate for other elements coming later in the optical

5   signal path.

The first and second beams can be combined at substantially the same location as where the optical signal was separated into the first and second beams, whereby the beams follow substantially the same path from beginning to end, and whereby the effects of spatially dependent imperfections in the component

10   assembly are substantially minimized.

The processing of the first and second beams may comprise equalizing the optical signal to generate an output from the component assembly which approximates a target power spectrum, the component assembly thereby comprising an equalizer which compensates for wavelength-dependent transfer

15   function variations in components prior to the component assembly in the optical signal path, wherein the component assembly comprises a plurality of filters and wherein each of those filters is associated with an element in a frequency-domain series approximation of a target transfer function, which for a given input signal will achieve a target output optical power spectrum. The

20   parameters of those filters can then be adjusted in order to improve the frequency-domain series, such as a Fourier series, approximation of the target

transfer function.   The adjusted parameters might be the amplitude or phase

coefficients. Further provided in an exemplary embodiment is a controller

operable to monitor the optical spectrum output from the equalizer and to adjust

parameters of at least one filter in order to control the filters so that the optical

5   spectrum output from the equalizer approximates a target power spectrum.

Control methods are also described above for controlling an optical harmonic

equalizer comprising a plurality of harmonic filters, the equalizer having an

optical signal input for receiving an input optical signal and an optical signal

output for transmitting an output optical signal. Certain of these methods

10   comprise determining a target power spectrum for the output optical signal,

measuring the power spectrum of the output optical signal, calculating the

difference between the measured power spectrum and the target power

spectrum, and adjusting at least one amplitude control voltage and at least one

phase control voltage associated with at least one of the plurality of harmonic

15   filters based on the difference between the measured power spectrum and the

target power spectrum.

The difference between the measured power spectrum and the target power

spectrum can be decomposed into a frequency-domain series approximation

wherein the frequency-domain series approximation is a Fourier approximation.

20   In the approximation, each element in the frequency-domain series

approximation is represented by a frequency-domain variable and at least one

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constant, and wherein each element in the approximation is associated with one of the plurality of harmonic filters. One approach for determining the constants associated with each element in the frequency-domain series approximation is to compute these constants in steps, beginning with the lowest-order series element and ending with the highest-order series element.

At each step prior to the last step when the frequency-domain constants are calculated in steps, beginning with the lowest-order element, a residual function is calculated at each step wherein the residual function is the remainder after subtracting the current frequency-domain series approximation from the target power spectrum, wherein the current frequency-domain series approximation includes the computed frequency-domain approximation elements which are known at that step.

The measuring, calculating, and adjusting actions can be repeated a plurality of times until the actual power spectrum reaches sufficiently close to the target power spectrum. The success in this approximation can be assessed by comparing the magnitude of the calculated difference to a predetermined threshold and repeating the measuring, calculating, and adjusting actions until the magnitude of the calculated difference is less than the predetermined threshold.

Another method for controlling an equalizer having at least one harmonic filter comprises determining a target transfer function for the equalizer, measuring an actual transfer function for the equalizer, calculating at least one amplitude constant and at least one phase constant for each of the at least one harmonic

5   filter, the amplitude and phase constants being calculated to adjust the actual transfer function of the equalizer to more closely approximate the target transfer function, and adjusting at least one amplitude control voltage and at least one phase control voltage to the at least one harmonic filter, wherein each of the at least one amplitude control voltages is dependent on a particular one

10   of the at least one amplitude constants, and wherein each of the at least one phase control voltages is dependent on a particular one of the at least one phase constants.

This method may include determining the target transfer function by measuring spectral energy of an input signal and subtracting the spectral energy of the

15   input signal from a target power spectrum. At least one amplitude constant and the at least one phase constant can be computed by decomposing the target transfer function into at least one Fourier component, wherein each of the at least one Fourier components is associated with a particular one of the at least one harmonic filters, and decomposing the actual transfer function into at least

20   one Fourier component, wherein each of the at least one Fourier components is associated with a particular one of the at least one harmonic filters, and

comparing the at least one Fourier component of the actual transfer function to the at least one Fourier components of the target transfer function, whereby using frequency-domain calculations it can be determined whether the actual transfer function has sufficiently approximated the target transfer function.

5   This process can be repeated for a certain number of iterations or until the target power spectrum or target transfer function is reached.

A controller can be provided to achieve these functions. This controller may include a processor for executing a plurality of executable instructions and a memory operable to store the plurality of executable instructions. The

10   executable instructions further comprise instructions which are operable to determine a target transfer function for the equalizer, calculate at least one amplitude constant and at least one phase constant for each of the at least one harmonic filters, the amplitude constant and phase constant being calculated to adjust the actual transfer function of the equalizer to more closely approximate

15   the target transfer function, and adjust at least one amplitude control voltage and at least one phase control voltage to the at least one harmonic filters, wherein each of the at least one amplitude control voltages is dependent on a particular one of the at least one amplitude constants, and wherein each of the at least one phase control voltages is dependent on a particular one of the at

20   least one phase constants.

The executable instructions may further comprise executable instructions which are operable to measure the spectral energy of an input signal and subtract the spectral energy of the input signal from a target power spectrum to determine the target transfer function of the equalizer. The controller may communicate

5   with an optical spectrum analyzer to measure the actual transfer function of the equalizer, and this actual transfer function may be effectively measured by the optical spectrum analyzer by measuring the power spectrum of an output optical signal and subtracting the spectral energy of the input signal.

Also described is a method for controlling a plurality of harmonic filters, the

10   method comprising determining a target transfer function, calculating a first sinusoidal function with a first amplitude constant and a first phase constant, wherein the first sinusoidal function approximates the target transfer function, calculating a residual equalization profile by subtracting the first sinusoidal function from the target transfer function, and calculating a second sinusoidal

15   function with a second amplitude constant and a second phase constant, wherein the second sinusoidal function approximates the residual equalization profile whereby the first and second sinusoidal functions added together more closely approximate the target transfer function than did the first sinusoidal function.

20   In this method, the determining the target transfer function may further comprise determining spectral energy associated with an input signal and

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subtracting the spectral energy from a target power spectrum. The calculating

of the first sinusoidal function may further comprise calculating a sinusoid with

a predetermined wavelength with the lowest least square error with respect to

the target transfer function. Other actions that may be a part of the method

5   include adjusting a phase control voltage based on the first phase constant and

adjusting an amplitude control voltage based on the first amplitude constant.

The phase control voltage may be applied to a first harmonic filter and the

amplitude control voltage may also be applied to the first harmonic filter,

wherein the first harmonic filter applies the first sinusoidal function to the input

10   signal to generate an output optical signal. A second phase control voltage and

a second amplitude control voltage may also be applied to a second harmonic

filter which will apply the second sinusoidal function to the input signal to

generate an output optical signal with the first harmonic filter.

A controller for controlling a plurality of harmonic filters is also described,

15   wherein the controller comprises a processor which is operable to execute a

plurality of executable instructions and a memory in communication with the

processor, the memory comprising the plurality of executable instructions

, wherein the plurality of executable instructions comprises instructions. The

executable instructions in this case may include instructions which determine a

20   target transfer function, calculate a first sinusoidal function with a first

amplitude constant and a first phase constant, wherein the first sinusoidal

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function approximates the equalization profile, calculate a residual equalization function, and calculate a second sinusoidal function with a second amplitude constant and a second phase constant, wherein the second sinusoidal function approximates the residual equalization function. Further, the instructions which

5   calculate the first sinusoidal function further comprise instructions which calculate a sinusoid with a predetermined wavelength with the lowest least square error with respect to the target transfer function. The instructions further may calculate the residual function by subtracting the first sinusoidal function from the target transfer function.

10   Also provided with the controller described above may be a plurality of executable instructions further comprise instructions which are operable to adjust a phase control voltage based on the first phase constant and adjust an amplitude control voltage based on the first amplitude constant.

In the above approach, the phase control voltage may be applied to a first

15   harmonic filter and the amplitude control voltage may also be applied to the first harmonic filter. The first harmonic filter then applies the first sinusoidal function to the input signal to generate an output optical signal.

The controller may also be operable with its executable instructions to calculate a second phase control voltage and a second amplitude control voltage to be

20   applied to a second harmonic filter, which will apply the second sinusoidal

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function to the input signal to generate an output optical signal with the first harmonic filter.

Further described is an optical system which is operable to receive an optical input signal, the optical system comprising an optical signal input, an optical signal output, a plurality of harmonic filter stages driven by a plurality of control voltages, and an optical path optically connecting the optical signal output to the optical signal input through the plurality of harmonic filter stages. The plurality of harmonic filter stages are operable to selectively attenuate by wavelength the optical signal carried on the optical path to thereby generate an equalized optical signal at the optical signal output. Also provided is an optical spectrum analyzer connected to the optical signal output and operable to receive the equalized optical signal and to measure the optical power spectrum of the equalized optical signal. A controller is further in communication with and operable to control the plurality of harmonic filter stages, the controller further in communication with the optical spectrum analyzer whereby the controller is operable to receive data representing a measurement of the optical power spectrum of the equalized optical signal and to compare that measured optical power spectrum to a target power spectrum. Based on the comparison, the controller adjusts the plurality of harmonic filter stages such that the attenuation imposed by the plurality of harmonic filters is adjusted to cause the power

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spectrum of the equalized optical signal to more closely approximate the target power spectrum.

The system may further comprise a memory connected to the controller, wherein the adjustments to the control voltages are made according to values stored in the memory which correlate certain elements of the Fourier series approximation to certain control voltages. The controller may be a digital signal processor. The system also can include a graphical user interface wherein an automatic control configuration section is provided for configuring a control algorithm for the plurality of harmonic filter stages. The automatic control configuration section further includes an output spectrum control section for configuring the controller to control the plurality of harmonic filter stages to output. The output signal thereafter is adjusted to approximate the target power spectrum.

To control the system, a controller is provided in communication with and operable to control the plurality of harmonic filter stages, the controller further communicates with the optical spectrum analyzer whereby the controller is operable to receive data representing a measurement of the optical power spectrum of the equalized optical signal and compares that measured optical power spectrum to a target power spectrum and adjusts the multiple stages of the equalizer such that the attenuation of the plurality of harmonic filters is

adjusted to cause the power spectrum of the equalized optical signal to more closely approximate the target power spectrum.

In this system, the controller may further measure the optical spectrum difference between the optical power spectrum of the output optical signal and the target power spectrum and decompose those differences into a Fourier series approximation. In this system, the plurality of control voltages are applied to the plurality of harmonic filter stages to adjust them according to the Fourier series approximation of the differences between the optical power spectrum of the output optical signal and the target power spectrum.

Also provided is a memory connected to the controller, wherein the adjustments to the control voltages are computed by the controller in accordance with an algorithm contained in executable instructions stored in the memory.

Further described is a Graphical User Interface ("GUI") for configuring an optical harmonic equalizer, which provides an output signal that is a wavelength compensated version of an input signal. The graphical user interface comprises an automatic control configuration section for configuring a control algorithm for the optical harmonic equalizer, the automatic control configuration section comprising a power spectrum control section for configuring the equalizer to form at its output an output signal which approximates a target power spectrum.

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The graphical user interface may include in an output spectrum control section at least two target inputs for configuring relative spectrum amplitudes of at least two wavelength regions within the target power spectrum. This section may include at least three target inputs for configuring relative spectrum amplitudes of at least three wavelength regions within the target power spectrum. Alternatively, this output spectrum control section may comprise a graphical input by which a user could graphically describe a target power spectrum which the user desires the equalizer to form at its output.

The GUI may also include performance indicator displays whereby a user can determine the relative success of the equalizer in approximating the target power spectrum.

The GUI may also include an input where the user can configure the equalizer to allow the input signal to pass through without equalization, thereby allowing an optical spectrum analyzer placed at the output of the equalizer to determine the power spectrum shape of the input signal so that the equalizer an be configured to compensate for gain variations with wavelength in prior optical components.

The GUI may also include a manual control section having a plurality of filter stage configuration fields whereby optical parameters can be set specifically and manually for each stage within the equalizer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram of an exemplary optical communication system;

FIGURE 2A is a graph of a first exemplary gain function and equalizer transfer function;

FIGURE 2B is a graph of a second exemplary gain function and equalizer transfer function;

FIGURE 3 is a block diagram of an exemplary equalizer having a single harmonic filter;

FIGURE 4 is a transfer function associated with the harmonic filter of FIGURE 3;

FIGURE 5 is a graph of a third exemplary gain function and equalizer transfer function;

FIGURES 6A-6B are block diagrams of an optical harmonic equalizer and associated control circuitry;

FIGURE 7 is an exemplary Graphical User Interface through which a user can configure an optical harmonic equalizer;

FIGURE 8 is a flow diagram describing the control of harmonic filters;

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FIGURE 9 is a flow diagram describing a technique for controlling multiple harmonic filters;

FIGURE 10 is a flow diagram describing another technique for controlling multiple harmonic filters;

5   FIGURE 11 is a conceptual diagram of a harmonic equalizer;

FIGURE 12 is a block diagram describing a first optical harmonic equalizer;

FIGURE 13 is a block diagram describing a second optical harmonic equalizer;

FIGURE 14 is a block diagram describing a third optical harmonic equalizer;

FIGURE 15 is a block diagram describing a fourth optical harmonic equalizer;

10   FIGURE 16 is a conceptualized diagram describing an optical tilter;

FIGURE 17 is another block diagram describing an optical tilter;

FIGURE 18 is another block diagram describing an optical tilter; and

FIGURE 19 is still another block diagram describing an optical tilter.

DETAILED DESCRIPTION

Referring now to **FIGURE 1**, there is illustrated a block diagram of an optical

network, referenced generally by the numeric designation 100. The optical

network 100 includes a fiber optic link 105 carrying thereon any number of

5   optical signals 110. Wavelength division multiplexing (WDM) and dense

wavelength division multiplexing (DWDM) provision any number of

wavelength channels for transmission of information. In WDM and DWDM

applications, carriers of differing optical wavelengths are transmitted in parallel

through the optical fiber link 105. In other words, the optical signals 110 will

10   comprise a number of optical carriers having differing wavelengths, and the

optical signals 110 will accordingly occupy a spectrum which is broader than in

prior single-wavelength systems. Thus, in the WDM and DWDM applications,

the wavelengths being transmitted through the optical system span a broader

range. In contrast to a single optical wavelength system, where a single discrete

15   carrier at one narrow wavelength is transmitted through the optical network, in

the WDM and DWDM case wavelength-dependent transmission effects begin

to take hold. The varying optical performance for different optical wavelengths

accordingly begins to affect the performance of the overall fiber transmission

network.

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As the fiber optic link 105 carries the signals110 for longer distances, the

signals 110 attenuate, making optical detection difficult. The strength of the

signals 110 is increased by an optical amplifier 115. An exemplary optical

amplifier 115 can comprise, for example, an Erbium Doped Fiber Amplifier

5   (EDFA). The optical amplifier 115 is characterized by a gain function, which

often varies with respect to input wavelength. Therefore, the optical amplifier

115 outputs an amplified signal 120, wherein the wavelength channels of the

WDM or DWDM signal # 120 are amplified by different factors. Specifically,

the EDFA would ideally amplify the entire spectrum of the incoming signal 110

10   by an equal amount, but because of the physical limitations of the amplifier, its

gain will vary with wavelength. This wavelength-dependent gain characteristic

is accentuated because of the greater bandwidth occupied by the signal 110

carrying multiple WDM or DWDM channels.

The amplified signal 120 is received by an Optical Harmonic Equalizer

15   ("OHE") 125. To compensate for varying gain among the different wavelength

channels of amplified signal 120, the equalizer 125 processes that amplified

signal 120, selectively attenuating particular wavelengths to yield at its output

an equalized signal 128 having, in one example, a substantially equivalent gain

among its wavelength channels relative to the incoming signal 110.

20   The equalization may be performed by imparting wavelength-dependent

filtering or gain upon the amplified signal 120, thus compensating for the

generally undesirable wavelength-dependent transmission functions of other

components in the optical signal path. For convenience in the embodiments

below, the equalization is generally described as being performed by

wavelength-dependant filtering or attenuation of the amplified signal 120, but it

5   should be understood that the equalization can also be performed in the

equalizer 125 by selectively amplifying certain portions of the power spectrum

of the amplified signal 120.

Referring now to **FIGURE 2A**, there is illustrated a graph describing an

exemplary output gain function 205 of the optical amplifier 115 with respect to

10   wavelengths 210. For example, optical amplifier 115 amplifies wavelengths in

the 1520–1570 nm wavelength range. An ideal optical amplifier 115 produces

a flat gain with respect to the wavelengths. The exemplary optical amplifier

115, however, produces a higher gain in higher wavelengths and a lower gain in

lower wavelengths, resulting in the exemplary output gain function 205. This is

15   known as tilted gain. Therefore, to compensate for this tilted gain, a transfer

function is applied by the equalizer 125 to the amplified signal 120, attenuating

the lower wavelengths to a lower degree and the higher wavelengths to a higher

degree. The preferred transfer function for the exemplary output gain function

205 is described by curve 215.

20   Alternatively, an optical amplifier 115 may produce lower gain in higher

wavelengths. Referring now to **FIGURE 2B**, there is illustrated a graph

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describing an alternative output gain function 220 of optical amplifier 115 with

respect to wavelengths 225. The optical amplifier 115 produces a higher gain in

lower wavelengths and a lower gain in higher wavelengths. Therefore, to

compensate the alternative output gain function 220, a transfer function 230 is

5   applied to the amplified signal 120 which attenuates the lower wavelengths to a

higher degree and the higher wavelengths to a lower degree.

Referring now to **FIGURE 3**, there is illustrated a block diagram of an

exemplary equalizer 125 which can be used to produce transfer functions to

compensate for tilted or more complexly varying gains among amplified signals

10   120. The equalizer 125 includes a beam displacer 319, a crystal 325, liquid

crystals 330, 335, and 340, polarizer or PBS 345, and a recombining element

350. The beam displacer 319 receives and separates the incoming light signal

120 into two orthogonally polarized light beams 303a-b. One of the light

beams, e.g., light beam 303a is propagated along the direction of the incoming

15   light signal 120, while the other light beam, e.g., light beam 303b is refracted

along another direction. At the output of the beam displacer, at the output of

beam 303a, a halfwave plate is provided to properly orient the polarization of

the beam 303a for its passage through subsequent elements in the optical path.

Each beam 303a-b is propagated through the crystal 325, and liquid crystals

20   330, 335, and 340. The crystal 325, and liquid crystals 330, 335, and 340,

polarizer 345 and recombining element 350 can be positioned in a manner to

receive directly the light beams 303a-b. Alternatively, light beam 303b can be redirected to these elements by a redirecting element (see, e.g. FIGURE 16, element 2145). Where the light beams are to be aligned in polarization with subsequent elements such as polarizing beam splitters or other polarization-dependent elements, halfwave plates or polarization rotators may be provided to rotate the polarization of one or both of the beams 303a-b.

The crystal 325 and liquid crystals 330, 335, and 340 collectively form a crystal set 365, i.e. a collection of one or more crystal elements, and in the embodiment shown in FIGURE 3, the crystal elements work together to impart controllable phase and amplitude changes upon the beams 303a-b which pass through the crystal set 365. For example, in the embodiment of FIGURE 3, the phase-altering liquid crystal 335 is controlled by the Vp voltage to impart a variable phase change upon the beams 303a-b. The phase-altering liquid crystal 335 imparts the phase change because of its voltage-variable retardation coefficient; in other words, the liquid crystal variably retards the phase of the beams according to the voltage applied to it. The amplitude-altering liquid crystals, 330,340 work by polarization-dependent coupling. An ideal polarization filter will pass 100% of a light beam which has a polarization exactly aligned with the polarization filter or polarizer and will pass 0% of a light beam which has a polarization exactly orthogonal to the polarization of the filter. Between the two extremes of 0% and 100%, a variable amount of light will pass through a

polarization filter according to the component of the polarization vector that is

aligned with the polarization filter. Because liquid crystals will twist the

polarization of an optical signal, a voltage, Va, can thus be used to variably

adjust the polarization of the beams passing through them according to the

5   voltage applied. The amplitude control voltage, Va, is applied in common or

differentially to both crystals of the amplitude-altering pair of liquid crystals

330,340.

Techniques for modulating amplitude and phase of optical signals can be

further understood by review of texts such as Bahaa E. A. Saleh and Malvin C.

10 Teich, FUNDAMENTALS OF PHOTONICS (John Wiley & Sons, Inc. 1991), which

is incorporated by reference herein.

Crystal set 365 together with polarizer 345 forms a harmonic filter 355 which is

operable to receive light which has been polarized by beam displacer 319. The

harmonic filter 355 selectively attenuates portions of an input light signal 120.

15 An equalizer 125 may use multiple cascaded harmonic filters 355 to define its

transfer function, as further described in FIGURE 5. Equalizers comprising a

single harmonic filter, like equalizer 125 of FIGURE 3, compensate for tilted

gain and therefore are sometimes referred to generally as "tilters."

The actual transfer function generated by another exemplary equalizer 125 is

20 illustrated in **FIGURE 4**. In this embodiment, the level of attenuation

performed by equalizer 125 varies sinusoidally with respect to wavelength as

illustrated by curve 405. The amplitude 410 and phase 415 of the sinusoidal

transfer function can be adjusted to implement a particular transfer function

such as, for example, equalizer transfer functions 215 and 230 illustrated in

5   FIGURES 2A-2B. The crystal 325 of harmonic filter 355 generally determines

the wavelength 420 of the sinusoid 405. The amplitude 410 is generally set by

the outer pair of amplitude-altering liquid crystals 330,340, which are

controlled by application of a control voltage VA, thereto. The phase 415 is

generally set by the inner, phase-altering liquid crystal 335. This liquid crystal

10   335 is controlled by application of a control voltage VP, thereto. In each case,

the control voltage is generally an analog control voltage, which serves to

adjust the amplitude or phase of the light beam passing through the appropriate

liquid crystals. The liquid crystals do not need to be arranged exactly as

described here. For example, the phase-altering liquid crystal 335 could be

15   positioned between the liquid crystal 330 and crystal 325.

The harmonic filter 355 uses crystal set 365 working with polarization beam

splitter 345 to remove unwanted harmonic components from beams 303a-b.

The beams 303a-b are then received by recombining element 350 which

recombines the beams 303a-b. The resulting signal is the equalized signal 128.

20   The target transfer function can be generated by the harmonic filter 125 by

adjusting the control voltages to control the amplitude 410 and phase 415 of the

sinusoid. For example, wherein the equalizer transfer function requires a lower

degree of attenuation for lower wavelengths, the amplitude 410 and phase 415

can be adjusted in a manner that the falling arm 417b of the sinusoid 405

coincides with the wavelengths amplified by the optical amplifier 115.

5   Alternatively, wherein the equalizer transfer function requires a higher degree

of attenuation for lower wavelengths, the amplitude 410 and phase 415 can be

adjusted such that the rising arm 417a of the sinusoid 405 coincides with the

wavelengths amplified by the optical amplifier 115.

Referring now to **FIGURE 5**, there is illustrated a graph of another exemplary

gain function 505 with respect to wavelength which can be associated with the

10   optical amplifier 115 for the 1520–1570 nm wavelength ranges. A preferred

transfer function to compensate for the gain response of this optical amplifier

115 is described by curve 510. For this type of gain response, the target

equalizer transfer function 510 cannot be accurately approximated by a portion

15   of a single sinusoid 405. The equalizer transfer function 510 is therefore

treated as a repeating function with a period equivalent to the range of the

optical amplifier 115. A periodic function with a finite period can be expressed

as a series of sinusoidal functions, wherein each of the sinusoidal functions has

a period equal to the finite period divided by an integer. The foregoing series

20   of harmonics comprises a frequency-domain series, which would include

Fourier series, and a given frequency domain series can be summed together in

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order to approximate a certain frequency domain signal. The summing of the

frequency-domain elements of the frequency-domain series comprises a

frequency-domain series approximation, which is the sum of a number of

functions of the form. Therefore, an ideal equalizer transfer function 510

5   which would compensate for prior optical element wavelength-dependent

transfer function variations can be approximated by the equalizer 125 through

the use of multiple harmonic filters 355.

Referring now to **FIGURES 6A-6B**, illustrated are block diagrams describing

an exemplary equalizer 125 which includes a number of harmonic filters

10   605(1)...605(N) cascaded with one another. An equalizer, which includes a

number of harmonic filters cascaded with one another, is known as an optical

harmonic equalizer. Each harmonic filter 605 selectively attenuates a portion

of a signal. The level of attenuation generally varies sinusoidally with the

wavelength of the signal, wherein the transfer function of the harmonic filter

15   are sinusoids with a period equal submultiples of the wavelength breadth of the

signal of interest from the optical amplifier or other optical element 115. In

other words, if the wavelength range of interest is 50 nm (such as for the C-

band range of 1520-1570 nm), then the period of the harmonic filters will be 50

nm, 25 nm, 16.667 nm, 12.5 nm, and 10 nm, etc.

20   Where "P" represents power and Tn represents the transfer function of the nth

harmonic filter, the following mathematically represents a mathematical

algorithm that can be applied to compute the necessary phase and amplitude

frequency-domain coefficients:

- For given target: $\Delta ref = P_{target} - P_{input} = 10\log_{10}(T1_{ref}) + \ldots + 10\log_{10}(T5_{ref})$.

- Based on Fourier analysis Δref can be decomposed as following:

5       $\Delta ref = C_{0(ref)} + \sum Cn_{(ref)} Sin(n\omega t + \theta n_{(ref)})$,

Where $Cn_{(ref)}$ & $\theta n_{(ref)}$ are magnitude and phase of Nth harmonic.

- For each harmonic component $Cn_{(ref)}Sin(n\omega t + \theta_{(ref)})$:

    (1)   The phase $\theta n_{(ref)}$ corresponds to the phase of transmission function Tn_{ref},

10   (2)   The magnitude $Cn_{(ref)}$ is generally proportional to the magnitude of transmission function Tn_{ref}.

An exemplary algorithm thus would be to monitor the output, using, for

example, an optical spectrum analyzer 660, measuring the transfer function of

15   the equalizer as the "delta" or Δ between the output power spectrum (P_{output})

and input power spectrum (P_{input}). The algorithm thus monitors the output

power spectrum and subtracts the input power spectrum to find the delta power

spectrum or transfer profile of the equalizer 125. The delta power spectrum is

then decomposed into its components as described above, and those

20   components can be compared to similarly decomposed components of the

reference or target transfer function of the equalizer (i.e., compare Δ and Δ_{ref}).

Based on the magnitude and phase comparison between these frequency-

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domain components, the algorithm adjusts the control voltages (as described

below) to each stage to make sub-harmonic components of same order be close

to each other. The net effect of having these sub-harmonic components of the

same order approach each other will be to also make the actual output power

5   spectrum approach the target output power spectrum.

Each of the harmonic filters 605(1)...605(N) are controlled by corresponding

amplitude control voltages, VA(1)...VA(N), and corresponding phase control

voltages VP(1)...VP(N). The amplitude control voltages VA(1)...VA(N)

control the amplitude 410 of the sinusoid 405 of the harmonic filter associated

10   therewith, while the phase control voltages VP(1)...VP(N) control the phase

415 of the sinusoid 405. By applying amplitude voltages VA(1)...VA(N) and

phase control voltages VP(1)...VP(N), equalizer 125 archives a selectively

determined transfer function, such as transfer function 510. The amplitude

control voltages VA(1)...VA(N), and the phase control voltages

15   VP(1)...VP(N) are applied by a controller 650, according to an algorithm or

look-up table values in a memory 680, and those values would generally be

predetermined at some point prior to operation of the control algorithm based

on the performance characteristics of the filter stages in the equalizer. In other

words, it might be determined that certain absolute values of voltages VA(1) ...

20   VA(N) and VP(1) ... VP(N) would impart certain phase shifts and amplitude

changes upon an incoming optical signal. Alternatively, it might be determined

30

that certain shifts in voltages would modify the phase shifts and amplitude

changes in a certain way. In either case, the effect of these voltage changes

upon the phase and amplitude of signals passing through the filter stages could

be algorithmically calculated as a part of the control algorithm, or they could be

5   determined as a part of that control algorithm by looking up the appropriate

voltage values based on the desired harmonic component changes.

Still referring to FIGURES 6A-6B, in a preferred approach, a DSP-based

control algorithm is used for providing the control voltages VP(1)...VP(N) and

VA(1)...VA(N). The algorithm runs on the controller 650, by drawing its

10   executable instructions from a memory 680, which may be an external memory

or a memory embedded within the controller itself. The same memory 680 or a

different memory can also be used to store temporary values used by the control

algorithm and the same memory 680 or a different memory can also be used for

storage of a look-up table correlating control voltage signals VA and VP to

15   desired frequency-domain coefficients of amplitude and phase (or magnitude

shifts relating to those components) within the equalizer's multiple filter stages.

A Graphical User Interface (GUI) 670 is provided through which a user can

configure or set parameters for the control algorithm.

The output of the equalizer 125 may be a flat, constant power level based on a

20   particular input signal, but other output levels may be sought after as well. This

"target equalization function" is a function of the system into which the

31

equalizer 125 is to be placed, according to other optical elements in the system. In order to achieve the target equalization function, the equalizer is configured based upon the input profile to achieve as nearly as possible the target equalization function. The target equalization is referred to here as the "target

5 transfer function," which essentially is the ideal equalization curve that the equalizer 125 is configured to approximate as nearly as possible. The actual equalization performance of the equalizer 125 is referred to as its "transfer function." The task of the control algorithm is to make the actual transfer function of the equalizer 125 as close as possible to the target transfer function.

10 The control algorithm preferably measures its success in approximating the target transfer function through the use of an optical spectrum analyzer 660, the output of which is provided to the GUI and in turn to the controller 650. The memory 680 stores the instructions, which are provided to the controller 650 through an interface 685 executable by the controller 650. The executable

15 instructions cause the controller 650 to operate as described with respect to these and subsequent figures in this specification.

While the control algorithm preferably operates on a DSP-based system as described above, it could also be run on a general-purpose microprocessor or other microcontroller. The controller 650 may be on one integrated circuit, and

20 the memory 680 can be on the same integrated circuit or on another one. The GUI is an optional means of configuring the control algorithms and providing

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parameters for the control algorithms' operation, but other non-GUI approaches

can be provided. Further, the user interface may be located remotely from the

controller 650 and/or the equalizer 125, such as through the Internet or through

another computer network. An exemplary GUI interface is illustrated in

5   FIGURE 7 and described in the accompanying text.

FIGURE 7 provides an exemplary GUI 670, which can be used to configure

the DSP-based control algorithm to be run on the controller 650. This GUI 670

preferably contains three major sections, which are automatic control

configuration section 710, a manual control configuration section 720, and a

10   "Serial Communications" section 730.

The automatic control configuration section 710 allows the user to configure

the control algorithm with variables, such as the number of iterations to be

used, through the input box 712. The automatic control configuration section

710 also provides an output spectrum control section, which allows for

15   configuration of the ideal equalizer 125 output to be flexible. Thus, the target

output power spectrum can be other than a flat, equalized line. For example

with the dB level section 714, two dB setting inputs, LEFT_dB and

RIGHT_dB, can be used to set the relative equalized output of the lower

wavelength (LEFT_dB) vs. the higher wavelength (RIGHT_dB). If LEFT_dB

20   is set equal to RIGHT_dB, then the target output to the equalizer will be a flat-

line output having no variation in its output spectrum in the

wavelength/frequency domain. If, however, the LEFT_dB is set higher than the

RIGHT_dB, then the target power spectrum of the equalizer will be tilted –

decreasing in gain from shorter wavelengths to longer wavelengths. If the

LEFT_dB is set to lower than the RIGHT_dB, then the target power spectrum

5   of the equalizer will be tilted the other way – increasing in gain from shorter

wavelengths to longer wavelengths. In this way, the target power spectrum of

the equalizer can be modified to pre-compensate for subsequent components in

the optical path, while the equalizer is still compensating dynamically for

changes in the gain of the amplifier which comes before it in the optical path.

10   Although this modification of the target power spectrum is described here as a

linear tilting of the target power spectrum, the equalizer configuration set-up

could be adapted to allow more refined pre-compensation. For example, there

could be a LEFT_dB, CENTER_dB, and RIGHT_dB input which would allow

the pre-compensation to be triangular (i.e., lower or higher in the center of the

15   wavelength band relative to both outputs). Alternatively, the inputs can be

adapted to allow linear tilts, which increase or decrease, over their relative

wavelength subsections. With additional inputs or with a graphical input, a

much more complicated pre-compensation could be defined into the target

power spectrum.

20   Within the automatic control configuration section 710, clickable targets 716

may be provided for determining whether the control algorithm runs

continually, upon clicking of the "Run" button, or in Steps, based on parameters

set using the preferred "Input," "Target," "Initial Value," and repeated pressing

of the "Iterate" button. The menu of clickable targets for the "Steps" approach

are found within the group of clickable targets 718. The advantage of using the

5   "Steps" approach is that it allows the user to see the effect of each iteration,

especially when the system is going through initial evaluations, this allows the

user to make sure that each iteration of the control algorithm is in fact moving

the actual power spectrum closer to the target power spectrum. The "Target"

button within the clickable targets 718 instructs the controller 650 to compute

10   the target transfer function based upon the power spectrum of the input optical

signal and the target power spectrum of the output optical signal. An "Initial

Value" button is provided by which the user instructs the controller 650 to

compute initial control voltages for the filters 605 according to an algorithm or

look-up table values (e.g., a "translator table"). These initial values may be

15   based on characterization data which was collected on the equalizer, for

example, at time of assembly/manufacture of the equalizer or at another time.

The initial values could also be based, alternatively or in addition to the

characterization data, on the power spectrum of the input optical signal.

The manual control section 720 allows a user to specify the values for the

20   amplitude factors 722 and phase shift factors 724 for each stage. In this

embodiment, there are five stages of filtering for the equalizer, although the

35

algorithm can be adapted for fewer or more stages. The Manual Control

section 720 also allows a user to manually specify the accuracy with which the

target power spectrum must be matched by using the clickable targets 726. The

manual control section 720 also gives a user great flexibility in troubleshooting

5   the equalizer 125. For example, by setting the amplitude adjusting coefficient to

"0" for each stage but one, the user can remove the effect of all the harmonic

filters 605 except for a single filter of interest, and then by varying the control

voltages to that single filter of interest, the user can assess the operation of the

singular harmonic filter 605.

10   The "Serial Communications" section 730 allows the GUI to interface with a

variety of optical spectrum analyzers 660 according to configurable interface

specifications with those analyzers. Other inputs can be provided here to allow

the GUI and the control algorithm to be more specifically customized

depending on the equipment and processors with which they communication.

15   Referring now to **FIGURE 8**, there is illustrated a flowchart describing the

control of the harmonic filters 605. At step 810, the amplified signal 120 is

examined and the power spectrum of the amplified signal 120, which is the

input signal to the equalizer 125, is measured. The GUI 670 is configured such

that it is possible to measure the input signal using only the optical spectrum

20   analyzer 660 at the output of the equalizer 125. This is done by selecting the

"Input" target 718, which allows the signal to pass through the equalizer 125

without influence of the filters contained in the equalizer, thereby giving the controller a baseline reference input signal power spectrum, which can be subtracted from the target output spectrum to arrive at a target transfer function for the equalizer.

5   At step 815, the target output power spectrum is determined based potentially on pre-compensation for subsequent elements in the optical signal path. The target output power spectrum is set according to the overall gain profile which is desired after all the optical components leading up to and through the equalizer 125, and this determination could also occur prior to initiation of the

10   algorithm shown in FIGURE 8, or it could be a default output power spectrum, such as a default flat output power spectrum.

During step 820, the actual output power spectrum (as opposed to the target output power spectrum) from the equalizer 125 is determined. The task of the control algorithm is then to control the equalizer 125 in order to make the actual

15   output power spectrum as close as possible to the target output power spectrum. Thus, at step 825, the target and actual output power spectra are compared. The comparison preferably breaks down the difference between the actual transfer function and the target transfer function into harmonic component values, such as Fourier harmonic component amplitude and phase constants. The control

20   algorithm will then at step 830 calculate desired phase and amplitude shifts for

each of these components such that the actual output power spectrum more closely matches the target output power spectrum.

When the control algorithm operates a multistage optical equalizer 125, it then controls those multiple stages according to the harmonic component value changes calculated in step 830. This is done at step 835 by dynamically controlling the control voltages to the individual stage filters 605 (1…N) within the equalizer 125. More specifically, at step 825 the difference between the target and actual output power spectra are calculated, and the signal is broken down in the frequency domain into harmonic components, the addition of which will in the aggregate approximate the target transfer function. The stages of the equalizer 125 can be set up to coincide with those harmonic components. According to those harmonic components of the difference between the target and actual output power spectra, the control algorithm will adjust the individual filter elements 605 (1…N) according to an algorithm or look-up table that correlates desired amplitude and phase constants, or amplitude and phase constant changes, with control voltages to the individual filters 605 (1…N).

At step 840, a determination is made whether to reexamine and readjust the amplitude and phase control voltages VA, VP, depending on whether the actual output power spectrum is close enough to the target output power spectrum, or the process can terminate after a certain number of iterations. The determination can be based, for instance, on whether the calculated amplitude

and phase voltages differences during step 830 are lower than a predetermined

threshold (perhaps by summing the squares of the amplitude harmonic

components of the difference between the target and actual output power

spectrum at the equalizer output). Alternatively, the determination can be made

5   after a predetermined number of iterations, or if the algorithm is failing to

converge toward the target output power spectrum. Wherein a determination is

made to reexamine and readjust the phase control voltages VA, VP, steps 820-

835 are repeated; otherwise the process ends.

Referring now to **FIGURE 9**, there is a flowchart describing another technique

10   for controlling the equalizer 125. Depending on where the power spectra are

measured, it may be desirable to use as a baseline measurement, the transfer

function of the equalizer 125, rather than using a target output power spectrum

as the benchmark. This technique describes a process for optimizing the

equalizer 125 to a "target transfer function" (Δ Ref), but it also describes other

15   techniques or steps which may be applied in the context of the FIGURE 8

discussion or in other contexts. Accordingly, the scope of the invention is set

forth in the claims to it and not in the specific embodiments described here.

The flowchart of FIGURE 9 provides an exemplary technique by which a

control algorithm adjusts the actual transfer function (Δ Real) of an equalizer

20   125 to approximate a target transfer function (Δ Ref) in the instance where an

optical harmonic equalizer 125 is controlled using Fourier series

approximations of the target transfer function (Δ Ref) and the actual transfer

function (Δ Ref), or a Fourier series approximation of a measured spectral

difference function between the target transfer function and equalizer transfer

function (Δ Ref - Δ Real).

5   In this technique, at step 905, the target transfer function (Δ Ref) is determined.

The target transfer function is determined by measuring the spectral energy of

the amplified signal 120 and subtracting the spectral energy of that input from a

target output power spectrum.

At step 907, the target transfer function, which is a theoretical transfer function

10   of the equalizer 125 for a given input which would produce the target output

power spectrum, is decomposed into a first harmonic series, such as a Fourier

series. The Fourier series representation of the signal comprises a series of

sinusoids, each of which are associated with a particular filter stage within the

equalizer, and each of which has a certain wavelength, amplitude, and phase.

15   At step 910, the spectral energy of the output signal is measured. The

difference between the spectral energy of the output signal and the input signal

is measured in step 915, yielding a measurement of the actual transfer function

of the equalizer 125. As with the system described in FIGURE 8, the difference

in spectral energy of the output signal and the input signal is indicative of the

level of attenuation with respect to wavelength provided by the optical

harmonic equalizer 125.

At step 925, the actual transfer function of the optical harmonic equalizer 125 is

decomposed into a second Fourier series, also represented by a series of

5   sinusoids with particular wavelengths, amplitude, and phases. The amplitudes

and phases of the first Fourier series are compared to the amplitudes and phases

of the corresponding elements in the second Fourier series for each wavelength

during step 930, and the differences are determined.

At step 935, the differences between the amplitudes and phases are compared in

10   the Fourier domain to a threshold to determine whether the actual transfer

function or attenuation of the optical harmonic equalizer 125 has converged

sufficiently to the target transfer function. For example, the mean square of the

differences can be compared to a predetermined threshold or the maximum

amplitude difference can be compared to a different predetermined threshold.

15   If the differences exceed the threshold, at step 940 each of the differences are

translated by the algorithm in order to effect voltage changes, where necessary,

to the control voltages VA(1)...VA(N), and VP(1)...VP(N). Those voltage

changes are applied to the filter stages at step 945.

Steps 910–945 are repeated in iterative fashion until the comparison at step 935

20   show the differences to be below the threshold – this threshold can be either a

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requirement that all or certain harmonic component differences are below a

certain value, or it could be based upon a sum-of-squares or other averaging

comparison to a threshold. In any case, once the threshold is greater than the

computed differences, the actual transfer function of the optical harmonic

5   equalizer 125 is deemed to be sufficiently close to the target transfer function,

and the output signal of the optical harmonic equalizer 125 would then provide

a sufficiently equalized amplified signal.

The foregoing control of the harmonic filters 605(1)...605(N) achieves the

target transfer function in an iterative manner. The harmonic filters

10   605(1)...605(N) are adjusted and the attenuation function is monitored until the

attenuation function approaches the target transfer function within a

predetermined threshold. The foregoing can be achieved within a certain

number of iterations, adjusting potentially all the filters at each iteration.

Alternatively, the harmonic filters 605(1)...605(N) can be adjusted one at a

15   time. This technique is described below with respect to FIGURE 10.

Referring now to **FIGURE 10,** there is illustrated a flowchart describing the

application of amplitude voltages VA(1)...VA(N), and phase control voltages

VP(1)...VP(N) to equalize an amplified signal 120, in another manner. The

control algorithm in this embodiment, like in FIGURE 9, determines a target

20   transfer function for the equalizer 125 and attempts to make the actual transfer

function of the equalizer 125 as close as possible to the target transfer function.

At step 1005, the target transfer function is determined. The target transfer function is determined by subtracting the spectral energy of the amplified signal 120, which is the input to the equalizer 125, to the actual output power spectrum from the target output power spectrum. This subtraction indicates the

5   shape of the equalization which is needed to yield the target output power spectrum, and therefore indicates the target transfer function. As before, the target output power spectrum may be a flat-line spectrum, or it may be linearly tilted or have a more complex shape to pre-compensate for subsequent optical elements in the optical signal path.

10   Each filter stage of the equalizer is capable (progressing from the first or lowest-frequency/longest-wavelength) stage to the Nth or highest-frequency/shortest-wavelength stage) of refining the degree to which the equalizer 125 approaches the target transfer function. The first stage provides the broadest approximation to the target transfer function, while each

15   subsequent stage adds further refinements to the prior approximation. Accordingly, it is possible to optimize the actual transfer function of the equalizer by successively bringing the different filter elements into the optical path filter by filter, from lowest-order element (e.g., n=1) to highest-order element (e.g., n=5 for a 5th-order harmonic filter).

20   At step 1010, the amplitude constant and phase constant of a sinusoidal function with a period equal to the wavelength of the first harmonic filter

605(1) is calculated which most closely approximates the target transfer

function. This calculation could be based, for example, on an algorithm which

minimizes the difference between the target transfer function and actual

transfer function according to the mean square error of the difference between

5   them.

At step 1020, the first-order approximation of the target transfer function,

which approximation is made by the first-order filter element in the equalizer

125, is subtracted from the target transfer function. This subtraction will yield

a residual equalization function which will comprise an error signal in the

10   difference between the first-order approximation and the target transfer

function. If subsequent filter stages can approximate the error signal, then

when the responses from those subsequent filter stages are added to the first-

stage filter response, the filters in the aggregate will more closely approximate

the target transfer function.

15   Thus, during step 1025, the amplitude constant and phase constant of a

sinusoidal function with a period equal to the wavelength of the next harmonic

filter, e.g., harmonic filter 605(2), is calculated which most closely

approximates the residual equalization function. At step 1028, this second filter

stage transfer function is subtracted from the first residual equalization

20   function, yielding a second residual equalization function. The second residual

equalization function will be the error signal between the second-order

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approximation and the target transfer function. Steps 1025–1028 are repeated

for each remaining harmonic filter 605(3)...605(N), as determined at step 1045.

At step 1055, the amplitude constant and phase constant calculated during the

preceding actions are translated into amplitude control voltages VA(1...N) and

phase control voltage VP(1...N), which are then applied to harmonic filters

605(1...N) at step 1058. The amplitude control voltages VA(1...N) and phase

control voltages VP(1...N) can be algorithmically defined or defined in a look-

up table in memory 680 or another memory. The translation between

amplitude/phase constants of the harmonic components and the control voltages

(VA and VP) may be based on theoretical values or may be configured on a

unit-by-unit basis depending on the actual performance characteristics of the

harmonic filters 605(1...N). Similarly, it is possible to determine all the values

algorithmically, applying all the values to the filter stages at one time at the end

of the process, or to iteratively determine one stage's values, apply the control

voltages to that stage, measure the actual residual, and then re-compute the

control voltages to be applied at the next stage based on the measured values.

As shown and described in FIGURE 3 and the accompanying text, the filtering

of the optical signal is performed in these embodiments by preferably

separating an optical signal into orthogonal components, i.e., a vertical and a

horizontal polarized component. For the previously described embodiments,

the relative paths of the two orthogonally polarized beams were not specified.

Each beam accordingly might propagate through the harmonic filters 605 from

input to output spatially through different paths. Because of spatially

dependent imperfections of optical components, however, resulting either from

the component fabrication or the materials used, the orthogonal beams may

5   behave differently depending on the optical paths which they traverse. This

behavioral difference can adversely affect the final performance of an optical

device, such as, for example, an optical equalizer or tilter. To alleviate these

imperfections, the following disclosure provides for the two beams to propagate

and counter-propagate an optical component assembly at the same spatial

10   locations. Various architectures for propagating and counter-propagating two

beams through a component assembly, i.e. an assembly of at least one optical

components or elements, may be employed. A component assembly may, for

example, comprise at least one harmonic filters 605 formed by using an

arrangement of crystal sets and polarization filters.

15   To address the concern regarding spatially dependant performance differences

between the orthogonally polarized beams as they traverse different routes

within an equalizer, architectures of the type disclosed in FIGURES 11-18 may

be used in conjunction with an equalizer having more than one harmonic filter

605. It should be appreciated, however, that the same architecture type may be

20   used in conjunction with a tilter, having one harmonic filter 605, as well as

other optical devices. The new-embodiment equalizers disclosed below can be

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used in the contexts described above by replacing the equalizer 125 in the

above contexts with the new-embodiment equalizers (1125, 1275, 1375, 1475,

1500, 2125, 2200, 2300, and 2400: See below figures.) These equalizers may

also be used in different contexts according to design needs. The common

5   approach in all of the embodiments below is to pass the spatially separated,

polarized components of the incoming beam 120 through the same optical path,

but in opposite directions through the common path. In this way, spatially

dependent effects (i.e., optical performance differences of the optical signal

passing through the equalizer components) are mitigated by having the optical

10   signals for both polarizations pass through the same path but in counter-

propagating directions.

Referring now to **FIGURE 11**, there is illustrated a conceptual diagram of an

exemplary optical equalizer 1125 in accordance with one possible embodiment.

This optical equalizer 1125 comprises a component assembly of a number of

15   optical components. As illustrated, the optical harmonic equalizer 1125

includes a polarization-based routing element 1130, beam displacers 1135a-b,

cascaded assembly 1140, and crystal set 1145. Cascaded assembly 1140

comprises a crystal set 1141 and a polarization filter 1142. At least one

additional cascaded assembly 1140, crystal sets 1145 and/or other elements may

20   be interposed between cascaded assembly 1140 and crystal set 1145. The

polarization-based routing element 1130 may comprise, for example, a

polarization beam splitter or another type of beam displacer such as a

birefringent element. Beam displacers 1135a-b may be PBSs or polarizing

glass. Crystal sets 1141 and 1145 may comprise liquid crystals, solid crystals,

or other optical components, such as waveplates, which alter the phase and/or

5   amplitude of an input beam. The beam displacers 1135a-b, the at least one

cascaded assemblies 1140, and the crystal set 1145 are disposed in a path 1150,

through which light beams 1155a and 1155b travel. The path 1150 is

terminated at both ends by polarization-based routing element 1130. It should

be appreciated that the path 1150 is preferably linear (as opposed to curved)

10   and is formed through the use of reflectors or other elements that guide a beam

from linear segment to segment. A reflector, such as, for example, a total

internal reflection element, may be used to achieve a linear feedback path. It

should also be appreciated that other elements may also be disposed along path

1150. All of the above described optical components and other components

15   can be used to comprise a component assembly which acts as an optical

equalizer in this or other embodiments described in this specification.

The polarization-based routing element 1130 separates amplified signal 120

into separate beams 1155a (indicated by dashed line) and 1155b (indicated by

solid line) which are orthogonally polarized with respect to one another. Beams

20   1155a-b are depicted side-by-side for illustrative purposes only. In practice,

each beam 1155a-b is propagated along the same spatial path 1150, or nearly

the same spatial path, but in opposite directions. Beam 1155a is propagated through beam displacer 1135a, at least one cascaded assemblies 1140, crystal set 1145, beam displacer 1135b, and back to polarization-based routing element 1130. Similarly, beam 1155b is propagated through beam displacer 1135b, crystal set 1145, a corresponding number of cascaded assemblies 1140, beam displacer 1135a, and back to polarization-based routing element 1130.

Each crystal set 1141 and 1145 is followed by a polarization filter 1142 or by a polarization-based beam displacer 1135a-b, and each crystal set/ polarization element pair collectively form a filter stage, which selectively attenuates certain wavelengths of the beams 1155a-b that are associated with high gain factors from amplifier 1110.

For the first beam 1155a, each of the cascaded assemblies 1140 forms a filter stage. Moreover, crystal set 1145 and beam displacer 1135b form another filter stage. For the second beam 1155b, the crystal set 1145 and the polarization filter 1142 of the first cascaded assembly 1140 form one filter stage. The crystal set 1141 of each cascaded assembly 1140 and the polarization filter 1142 of the next cascaded assembly 1140 form additional filter stages. The crystal set 1141 of the last cascaded assembly 1140 and the beam displacer 1135a form an additional filter stage.

The optical circuit of FIGURE 11 operates by splitting the incoming beam 120

into its vertical and horizontal polarizations and passes those horizontally and

vertically polarized beams in opposite directions through the same optical

components over the same path, but in different directions. In this manner, the

5   spatially dependent optical propagation effects induced by the equalizer are

minimized.

Referring now to **FIGURE 12**, there is illustrated a block diagram of an

exemplary optical harmonic equalizer 1275 in accordance with a first

embodiment. As described above, this embodiment splits an incoming optical

10   signal 120 into two beams 1230a-b comprising the vertical and horizontal

polarizations of the incoming optical signal 120. This is done to overcome the

spatially dependent imperfections which may exist in the optical components

used to form the equalizer 1275. Specifically, imperfections in the components

of equalizer 1275 can be caused by various characteristics of the materials or

15   the fabrication process. These imperfections can result in slightly differing

optical properties at differing locations within each component. Propagating

the polarized beams 1230a-b through the components of equalizer 1275 at the

same spatial locations within each component causes the effect of the foregoing

differing optical properties to be minimized and improves the performance of

20   the optical equalizer 1275 and the quality of the equalized signal 128.

The optical harmonic equalizer 1275 includes a polarization beam splitter (PBS) 1205. Polarization rotators 1210a-b are disposed adjacent to the PBS 1205 and along path segments which are orthogonal to one another. Polarization rotator 1210a is also adjacent to a PBS 1215a while polarization

5   rotator 1210b is also adjacent to a PBS 1215b. The PBS 1205, polarization rotator 1210a, and PBS 1215a are positioned substantially colinearly along a first path segment 1213a. PBS 1205, polarization rotator 1210b and PBS 1215b are also positioned substantially colinearly along a second path segment 1213b. In the illustrated embodiment, the polarization rotators 1210a-b are Faraday

10   rotators, which polarize beams passing through them in one direction, while leaving unaffected beams passing through them in the opposite direction.

Adjacent to PBS 1215a are at least one crystal sets 1220 and at least one PBS 1225 positioned in cascade and alternating with respect to one another, such that the cascade begins with a crystal set 1220 and ends with a terminating PBS

15   1225. Each crystal set 1220 includes liquid crystals 1221 and at least one solid crystal 1223, which together alter the phase and/or amplitude of incoming light beams. OHE 1275 illustrated in FIGURE 12 includes crystal set 1220a and PBS 1225a followed by crystal set 1220 b and PBS 1225b positioned substantially colinearly along a third path segment 1213c, which is substantially

20   at a right angle to the first path segment 1213a and parallel to the second path segment 1213b.

Similarly, adjacent to PBS 1215b are at least one crystal sets 1220 and at least

one PBS 1225, positioned in cascade and alternating with respect to one

another, such that the cascade begins with a crystal set 1220 and ends with a

terminating PBS 1225. OHE 1275 illustrated in FIGURE 12 includes crystal

5   set 1220c and PBS 1225c followed by crystal set 1220d and PBS 1225d

followed by crystal set 1220e and PBS 1225b positioned substantially

colinearly along a fourth path segment 1213d, which is substantially at a right

angle to the second path segment 1213b and parallel to the first path segment

1213a.

In operation, the optical harmonic equalizer 1275 receives the amplified signal

10   120 at PBS 1205. PBS 1205 splits the incoming beam into two orthogonally

polarized beams, 1230a-b. Beam 1230a generally propagates along path 1213

in a forward propagation direction 1214a. Beam 1230b generally propagates

along path 1213 in a reverse propagation direction 1214b. For example, beams

15   1230a-b are each guided along first and second spatial path segments 1213a and

1213b, respectively, through respective first and second polarization rotators

1210a and 1210b. Polarization rotator 1210a rotates the polarization of beam

1230a by ninety degrees. As a result, beam 1230a has the same polarization as

beam 1230b. Beam 1230b propagates through polarization rotator 1210b in

20   reverse direction. As a result, the polarization of beam 1230b is not altered.

The beams 1230a-b are then received by PBS 1215a and 1215b, at points 1235a

and 1235b, respectively. PBS 1215a directs beam 1230a through crystal set

1220a, PBS 1225a, and crystal set 1220b to path-segment terminating PBS

1225b along path segment 1213c. PBS 1215b directs beam 1230b through

5   crystal set 1220c, PBS 1225c, crystal set 1220d, PBS 1220d, and crystal set

1220e to path-terminating PBS 1225b along path segment 1213d. As noted

above, the crystal sets 1220 selectively alter the phase and amplitude of the

beams 1230a-b. The combination of each crystal set 1220/PBS 1225 pair

therefore forms a filter stage.

10   Path-segment terminating PBS 1225b is positioned to receive both beams

1230a-b at a particular point 1235c. The terminating PBS 1225b separates the

additional, unwanted harmonic components from the beams 1230a-b, wherein

the additional harmonic components are passed through the PBS 1225b and are

thereby not reflected onto the next path segment. Beam 1230a is directed by

15   PBS 1225b along path segment 1213d through crystal sets 1220c-e and PBSs

1225c-d. PBS 1215b receives beam 1230a at point 1235b. Beam 1230b is

directed along path segment 1213c through crystal sets 1220a-b and PBS

1225a. PBS 1215a receives beam 1230b at point 1235a.

PBS 1215b receives beam 1230a along spatial path segment 1213d at point

20   1235b and directs beam 1230a along spatial path segment 1213b through

polarization rotator 1210b to the PBS 1205. Similarly, PBS 1215a receives

beam 1230b along spatial path segment 1213c at point 1235c and directs beam

1230b along spatial path segment 1213a through polarization rotator 1210a to

the PBS 1205. As beam 1230a passes through the second polarization rotator

1210b, the polarization is rotated back by ninety degrees, thereby resulting in

5   the same polarization it had prior to passage through the first polarization

rotator 1210a, which had originally rotated the polarization of the beam by

ninety degrees when the beam passed through in the other direction. PBS 1205

combines the polarized beams 1230a-b to generate an equalized signal 128 as

an output.

Polarized beams 1230a and 1230b each propagate through the components of

10   optical equalizer 1275 along the same spatial paths 1213a-d as beam 1230b, but

in an opposite direction of propagation. The beams 1230a-b are shown side-by-

side for illustrative purposes only. In practice, they would propagate along

identical or nearly identical spatial paths. Guiding the polarized beams 1230a-b

15   along the same spatial paths as each other causes the polarized beams 1230a-b

to traverse the same components of OHE 1275 in the same spatial locations.

The minimization of the effects caused by spatially dependent imperfections in

the optical equalizer serves to reduce the Polarization Dependent Loss (PDL)

which is otherwise introduced by polarization-dependent effects in the optical

20   components.

Referring now to **FIGURE 13**, there is illustrated a block diagram of another

embodiment of an optical equalizer. The optical harmonic equalizer 1375

includes an optical component 1301 which in turn comprises a PBS 1305 and at

least two reflective surfaces 1310a and 1310b. The reflective surfaces 1310a-b

5   are disposed on opposite sides of the PBS 1305, and serve to reflect beams

striking them from within the optical component 1301. A Faraday rotator

1315a is positioned along a first signal path segment 1313a. Polarization

rotator 1315b is positioned along a second signal path segment 1313b.

Adjacent to polarization rotator 1315a are any number of PBSs 1325 and any

10   number of crystal sets 1320. The PBSs 1325a and crystal sets 1320a are

positioned in a cascaded arrangement and are alternating with respect to one

another, such that the cascade begins and ends with a PBS 1325. Similarly,

adjacent to polarization rotator 1315b are any number of PBSs 1325 and any

number of crystal sets 1320 connected in cascade and alternating with respect

15   to one another, such that the cascade begins and ends with a PBS 1325.

The optical equalizer 1375 receives the amplified signal 120 at optical

component 1301. The signal 120 enters the optical component 1301 and

continues to the PBS 1305 within the optical component 1301. The PBS 1305

splits the incoming beam into two orthogonal polarized beams 1350a-b.

20   Polarized beam 1350a is guided from PBS 1305 along spatial path segment

1313a through polarization rotator 1315a. Because beam 1350a goes through

the polarization rotator 1315a in the reverse direction, it is unaffected. Beam 1350a is thereafter guided through at least one PBSs 1325 and at least one crystal sets 1320.

Beam 1350b is reflected by the PBS 1305 to reflective surface 1310b, where it is received and reflected at point 1322d. At point 1322d, reflective surface 1310b reflects polarized beam 1350b along spatial path segment 1313b through polarization rotator 1315b, which rotates polarized beam 1350b by 90 degrees. The beam 1350b passes through at least one PBSs 1325 and at least one crystal sets 1320. As noted above, each crystal set 1320/PBS 1325 pair forms a filter stage.

A reflective element 1330 receives beam 1350a at point 1322b and reflects beam 1350a to point 1322c. At point 1322c, the element 1330 reflects polarized beam 1350a along spatial path segment 1313b through crystal sets 1320, PBSs 1325, and polarization rotator 1315b, to PBS 1305. The reflective element 1330 receives polarized beam 1350b at point 1322c and reflects beam 1350b to point 1322b. At point 1322b, the reflective element 1330 reflects polarized beam 1350b along spatial path segment 1313a through crystal sets 1320, PBSs 1325, and polarization rotator 1315a. The polarization rotator 1315a rotates the polarization of beam 1350b back by ninety degrees, thereby resulting in the same polarization of beam 1350b that it had prior to its initial passage through polarization rotator 1315b.

Polarizing beam splitter 1305 receives polarized beams 1350a and 1350b and

combines the polarized beams 1350a and 1350b, thereby resulting in equalized

signal 128. Equalized signal 128 is guided to point 1322a of reflective surface

1310a and reflected. Guiding the polarized beams 1350a-b to traverse the same

5   spatial locations within the PBS 1325 and crystal sets 1320 causes the effects of

the differing optical properties due to imperfections in the materials and

fabrication to be minimized. Accordingly, the performance of the optical

harmonic equalizer 1375 and the quality of the equalized signal 128 are

improved.

Referring now to **FIGURE 14**, there is illustrated a block diagram of an

exemplary optical equalizer 1475 in accordance with another embodiment. The

optical harmonic equalizer 1375 includes an optical component 1401 which in

turn comprises a PBS 1405 and at least two reflective surfaces 1410a and

1410b.

15   The optical harmonic equalizer 1475 includes a beam displacer 1402a adjacent

to the PBS 1405. The beam displacer 1402 may be a birefringent element or

other element which is operable to spatially decompose an incoming signal into

components parts. Polarization rotator 1415a is positioned along a first spatial

signal path segment 1413a. Polarization rotator 1415b is positioned along a

20   second spatial signal path segment 1413b.

Adjacent to polarization rotator 1415a are at least one of PBSs 1425 and crystal

sets 1420. The PBSs 1425 and crystal sets 1420 are positioned in a cascaded

arrangement and are alternating with respect to one another, such that the

cascade begins and ends with a PBS 1425. Thus, to form a single filter stage

5   along the signal path, there would be a crystal set 1420 interposed between a

pair of PBSs 1425. Each PBS 1425 acts with the crystal set that precedes it in

the optical path to form a harmonic filter. This is one reason why in the single-

stage harmonic filter embodiment, there is a PBS 1425 positioned on each side

of the crystal set 1420, so that one PBS 1425 acts with the crystal set 1420 for

10   the beam proceeding in one direction and the other PBS 1425 acts with the

crystal set 1420 for the beam proceeding in the other direction. The PBSs or

polarization filters 1425 further serve to isolate the plurality of harmonic filter

stages in an embodiment having a plurality of stages. The general description

of the arrangement of PBSs or polarization filters here also can be applied in

15   other embodiments set forth in this specification.

The polarization rotator 1415a, at least one of PBSs 1425, and at least one of

crystal sets 1420 are disposed along a substantially straight line (spatial path

segment 1413a). The polarization rotator 1415b, at least one of PBSs 1425, and

at least one crystal sets 1420 are disposed along another substantially straight

20   line (spatial path segment 1413b). Also disposed along both lines is a reflective

element 1430.

The optical equalizer 1475 receives the amplified signal 120 at a beam

displacer 1402a. The beam displacer 1402a spatially displaces the amplified

signal 120 resulting in polarized beams 1450a-b. Beams 1450a-b are received

by PBS 1405, which propagates beam 1450a and reflects beam 1450b toward

reflective surface 1410b. Reflective surface 1410b receives polarized beam

1450b at point 1422d and reflects beam 1450b along spatial path segment

1413b through polarization rotator 1415b, at least one PBSs 1425 and crystal

sets 1420 to point 1422c of reflective element 1430. Beam 1450a is propagated

by PBS 1405 along path segment 1413a through polarization rotator 1415a, one

or more PBSs 1425, and crystal sets 1420 to point 1422b of reflective element

1430.

Element 1430 receives polarized beam 1450a at point 1422b and reflects

polarized beam 1450a to point 1422c, where reflective element 1430 reflects

polarized beam 1450a along spatial path segment 1413b through crystal sets

1420 and PBSs 1425 and polarization rotator 1415b to point 1422d of reflective

surface 1410b. Reflective surfaces 1410b and 1410a reflect beam 1450a to

beam displacer 1402b.

Element 1430 receives beam 1450b at point 1422c and reflects beam 1450b to

point 1422b, where element 1430 reflects beam 1450b along spatial path

segment 1413a through crystal sets 1420, PBS 1425, and polarization rotator

1415a. Polarization rotator 1415a rotates the polarization of beam 1450b back

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by ninety degrees, thereby resulting in the same polarization of beam 1450b that

it had prior to its passage through polarization rotator 1415b. Beam 1450b

strikes PBS 1405 and is reflected to point 1422e. At point 1422e, polarized

beam 1450b is reflected to beam displacer 1402b. Beam displacer 1402b

5   receives the polarized beams 1450a-b and combines them, thereby resulting in

an equalized signal 128.

Guiding polarized beams 1450a-b to traverse the same spatial locations within

crystal sets 1420 and the PBSs 1425 causes the effects of the differing optical

properties due to imperfections in the materials and fabrication to be

10   minimized. Accordingly, the performance of the optical harmonic equalizer

1475 and the quality of the equalized signal 128 are improved.

Referring now to **FIGURE 15**, there is illustrated a block diagram of an

exemplary optical harmonic equalizer 1500 in accordance with another

embodiment. This equalizer employs a pair of beam-displacing prisms or

15   rhomboid prisms 1520,1525, which have internal surfaces which transmit,

undeflected, light passing in one direction, while reflecting light passing

through in the other direction. These rhomboid prisms serve as redirecting

elements in the disclosed embodiments.

For brevity, the beam-displacing prisms are referred to below as "rhomboids,"

20   which is the specific shape of the most-common embodiment of these optical

elements, but it should be understood that beam-displacing prisms of other shapes are contemplated.

The optical harmonic equalizer 1500 includes an incoming-signal beam displacer 1510 with an attached halfwave plate 1511, and an outgoing-signal

5   beam displacer 1514 with an attached halfwave plate 1516. These beam displacers 1510,1514, are placed on one side of rhomboid 1520, and a first polarization rotator 1521 is interposed between the incoming signal beam displacer 1510 and the rhomboid 1520. The second rhomboid 1525 is positioned adjacent to the first rhomboid 1520, but on the opposite side from

10   the two beam displacers 1510,1514. A second polarization rotator 1523 is interposed between the first rhomboid 1520 and the second rhomboid 1525.

Along a first spatial signal path segment 1513a, and adjacent to the second rhomboid 1525, are at least one PBSs 1535, at least one crystal sets 1530. These PBSs 1535 and crystal sets 1530 are connected in cascade and alternating

15   with respect to one another, such that the cascade begins and ends with a PBS 1535.

Along a second spatial signal path segment 1513b, which is parallel to the first spatial signal path segment 1513a, and also adjacent to the second rhomboid 1525, are at least one PBSs 1535 and at least one crystal sets 1530. The at least

20   one PBSs 1535 and at least one crystal sets 1530 are connected in cascade and

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alternating with respect to one another, such that the cascade begins and ends with a PBS 1535. Signal path segment 1513b, like signal path segment 1513a, terminates at reflective element 1540.

In operation, the equalizer 1500 receives the amplified signal 120 at the beam displacer 1510, which splits the incoming beam into two polarized beams 1515a (indicated as a solid line) and 1515b (indicated as a dashed line). The polarization of beam 1515a is rotated ninety degrees by halfwave plate 1511 so that it has the same polarization at as beam 1515b. Both beams 1515a and 1515b then pass through a Faraday rotator 1521 in the reverse direction so the rotator has no effect. Polarization rotator 1521 is provided to filter out back-reflected optical signals returning from the filtering elements – small components of which might pass back through the beam displacer 1510 and degrade the incoming signal through reflections.

After passing through polarization rotator 1521 unaffected, beam 1515a is guided through rhomboid 1520, polarization rotator 1523 (in the reverse direction, leaving the beam unaffected), rhomboid 1525, and along spatial path segment 1513a through crystal set(s) 1530, PBS(s) 1535 and reflective element 1540.

Beam 1515b passes unchanged through polarization rotator 1521 and the first rhomboid 1520. The polarization of beam 1515b is rotated by ninety degrees

upon exiting the first rhomboid 1520 by halfwave plate 1543. The second

polarization rotator 1523 also leaves beam 1515b unaffected in its first pass

through that polarization rotator 1523, since the beam 1515b passes through in

the reverse direction. The beam 1515b is then received at the second rhomboid

5 1525 at surface 1555a and reflected to surface 1555b, at which point it is

reflected into alignment with second spatial path segment 1513b. The

polarization of beam 1515b is rotated again by ninety degrees by halfwave plate

1546. This polarization rotation allows the polarized beam 1515b to have the

proper orientation to pass through crystal set(s) 1530 and PBS(s) 1535 to

10 reflective element 1540.

The polarized beams 1515a-b are then received by reflective element 1540. The

polarized beam 1515a is received at a point 1540a while polarized beam 1515b

is received at a point 1540b. The reflective element 1540 reflects the polarized

beam 1515a from point 1540a to point 1540b. At point 1540b, polarized beam

15 1515a is reflected along path segment 1513b, traversing through PBS(s) 1535

and crystal sets 1530 in the opposite direction from the travel of beam 1515a

through these same elements. Halfwave plate 1546 rotates the polarization of

beam 1515a such that at point 1555b, polarized beam 1515a is reflected to point

1555a, and at point 1555a, beam 1515a is reflected to polarization rotator 1523

20 and half wave plate 1543. Polarization rotator 1523 and halfwave plate 1543

rotate the polarization of beam 1515a such that rhomboid 1520 reflects signal

1515a toward beam displacer 1514. In particular, polarized beam 1515a passes

through halfwave plate 1517 to beam displacer 1514. Because of the

polarization rotation imposed by the halfwave plate 1517, beam 1515a. is

refracted in the beam displacer 1514, such that it will be combined with

5   polarized beam 1515b, which has followed a path described below.

The reflective element 1540 reflects polarized beam 1515b from point

1540b to point 1540a. At point 1540a, polarized beam 1515b is reflected along

path segment 1513a through PBS(s) 1535, crystal sets 1530, and rhomboid

1525 to polarization rotator 1523 that rotates the polarization of beam 1515b

10   such that rhomboid 1520 reflects beam 1515b toward beam displacer 1514. In

particular, beam 1515b passes through halfwave plates 1517 and 1516 such that

beam displacer 1514 combines polarized beams 1515a-b, thereby resulting in

equalized output signal 128.

Beams 1515a-b are depicted side-by-side for illustrative purposes only. In

15   practice, the beams 1515a-b are propagated along identical or nearly identical

spatial paths, but in opposite directions. Guiding the polarized beams 1515a-b

along the same spatial paths minimizes the effect of the varying optical

properties of components, with respect to spatial location, and thereby improves

the performance of the equalizer 1500 and the quality of the equalized signal

20   128.

Embodiments of the types disclosed in FIGURES 16-19, described below, may

be used in conjunction with a tilter having a single harmonic filter 605. It

should be appreciated, however, that the same architecture type may be used in

conjunction with equalizers having multiple harmonic filters 605, as well as

5   with other optical devices.

Referring now to **FIGURE 16**, there is illustrated a conceptual diagram

describing an exemplary optical tilter 2125 in accordance with one

embodiment. The optical tilter 2125 includes a beam displacer 2140 acting as a

separating element, redirecting element 2145, polarization filter 2150a, crystal

10   set 2155, polarization filter 2150b, and beam displacer 2175 acting as a

combining element. The polarization filters 2150a-b may comprise, for

example, polarization beam splitters (PBSs) or polarizers. The redirecting

element 2145 may comprise, for example, a rhomboid or a beam displacer. The

beam displacer 2140 separates an incoming amplified signal 120 into two

15   orthogonal beams: beam 2165a and beam 2165b. A redirecting element 2145 is

positioned to receive and propagate beams 2165a and 2165b.

Beams 2165a and 2165b are propagated along spatial path 2170 in opposite

directions, 2170a and 2170b, respectively. The crystal set 2155 is disposed

along path 2170 and alters the phase and/or amplitude of beams 2165a-b.

20   Crystal set 2155 and polarization filter 2150a form a filter, preferably a Fourier

harmonic filter, for beam 2165a. Crystal set 2155 and polarization filter 2150b

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form a filter, preferably a Fourier harmonic filter, for beam 2165b. After

propagating along spatial path 2170, the beams 2165a and 2165b are received

by redirecting element 2145 and guided to the beam displacer 2175, which

serves as a combining element. The beam displacer 2175 combines beams

5   2165a and 2165b, thereby resulting in equalized signal 128.

It should be appreciated that the path 2170 is actually linear (as opposed to

curved) and is formed through the use of reflecting or refracting elements

and/or fiber, which pass a beam from linear segment to segment. A reflector,

such as, for example, a Total Internal Reflection (TIR) element, may be used to

10   achieve a linear feedback path. Additionally, other elements not illustrated may

also be placed along path 2170. Furthermore, a single component can serve in

place of more than one of the above elements. For example, beam displacer

2140 may also be designed so as to also perform the combining function of

beam displacer 2175.

15   Imperfections in the components can be caused by materials or the fabrication

process. The foregoing can result in slightly differing optical properties at

differing locations within the component. However, guiding the polarized

beams to traverse the same spatial locations within the components causes the

effect of the foregoing differing optical properties to be minimized and

20   improves the performance of the optical tilter and the quality of the equalized

signal 128.

Referring now to **FIGURE 17**, there is illustrated a block diagram of an

exemplary optical tilter 2200. Optical tilter 2200 includes a beam displacer

2210 with an attached halfwave plate 2215. A beam-displacing prism or

rhomboid 2221 is disposed adjacent to the beam displacer 2210, followed by

5   polarization rotator 2220, PBS 2225, crystal set 2230, and reflective element

2235. A halfwave plate 2237 is also attached to rhomboid 2221 at the point

where the beams exit the rhomboid 2221 heading toward the second beam

displacer 2240 which serves as a combining element for the two polarizations

of the beam 2250. The second beam displacer 2240 has an attached halfwave

10   plate 2245 through which beam 2250a travels as it enters the second beam

displacer 2240.

In operation, the beam displacer 2210 receives amplified signal 120 and

separates it into two orthogonally polarized beams: beam 2250a and beam

2250b. The halfwave plate 2215 rotates the polarization of beam 2250b by

15   ninety degrees, thereby giving it the same polarization as beam 2250a, but

traveling over a different path. Beams 2250a and 2250b are passed through

rhomboid 2221. Beams 2250a and 2250b are propagated along spatial paths

2255a and 2255b, respectively, through a Faraday rotator 2220, PBS 2225, and

crystal set 2230. The Faraday rotator 2220 is arranged such that it will not

20   affect the polarization of beams 2250a-b while they are propagating toward

reflective element 2235, but will rotate the polarization of beams 2250a-b on

the return trip from the reflective element 2235.

Beams 2250a-b are then received by reflective element 2235. The polarized

beam 2250a is received at a point 2260a while polarized beam 2250b is

5   received at a point 2260b. The reflective element 2235 directs the polarized

beam 2250a from point 2260a to point 2260b. At point 2260b, polarized beam

2250a is directed along path 2255b through crystal set 2230 and PBS 2225.

The reflective element 2235 directs polarized beam 2250b from point 2260b to

point 2260a. At point 2260a, polarized beam 2250b is directed along path

10   2255a through crystal set 2230 and PBS 2225. Beams 2250a-b are received at

polarization rotator 2220. The polarization rotator 2220 rotates the polarization

of each beam 2250a-b.

Polarized beams 2250a-b are then received at rhomboid 2221 at points 2265a

and 2265b, respectively. Polarized beam 2250a is directed from point 2265a to

15   point 2270a. At point 2270a, polarized beam 2250a is directed through

halfwave plates 2237 and 2245. Each halfwave plate rotates the polarization of

beam 2250a by ninety degrees, thereby resulting in no change in polarization.

Polarized beam 2250b is directed from point 2265b to point 2270b. At point

2270b, polarized beam 2250b is directed through halfwave plate 2237 to beam

20   displacer 2240. Halfwave plate 2237 rotates the polarization of beam 2250b by

ninety degrees. Beam displacer 2240 combines polarized beams 2250a-b,

thereby resulting in equalized signal 128.

The polarized beams 2250a-b are guided through the components, e.g., the

crystal set 2230 and PBS 2225, along the same spatial paths 2255a-b, but in

5   opposite directions. Although beams 2250a-b are depicted side-by-side for

illustrative purposes, in practice, each beam 2250a-b is propagated along

identical or coextensive spatial paths or along parallel, adjacent spatial paths,

but in opposite directions. Guiding the polarized beams 2250a-b along

coextensive or nearly coextensive spatial paths causes the polarized beams

10   2250a-b to traverse the same spatial locations, thereby minimizing the effect of

the varying optical properties of the components. Also, by reflecting the beams

back through the same components and essentially re-using those components,

a second-order filter is built using fewer components than would otherwise be

required.

15   Referring now to **FIGURE 18**, there is illustrated a block diagram of an

another embodiment of an optical tilter 2300. Optical tilter 2300 includes an

input beam displacer 2310 and a halfwave plate 2311. Optical tilter 2300

further includes an output beam displacer 2314 and a halfwave plate 2316. A

beam-displacing prism or rhomboid 2320 is positioned adjacent to both beam

20   displacers 2310, 2314. A second beam-displacing prism or rhomboid 2325 is

positioned adjacent to rhomboid 2320. A Faraday rotator 2321 is positioned

between rhomboids 2320 and 2325.

The second rhomboid 2325 passes two signal paths on the side opposite from

the polarization rotator 2321. Both of these paths terminate at a reflective

5   element 2340, which as in prior embodiments serves to send a signal 2315a

arriving on a first signal path segment 2323a back onto a second signal path

segment 2323b and to reflect a signal 2315b arriving on the second path

segment 2323b back onto the first signal path segment 2323a.

In this embodiment, there is a crystal set 2330 and a polarization beam splitter

10   2335 positioned along second path segment 2323b. Halfwave plates 2343 and

2346 are positioned on opposite sides of rhomboid 2325.

In operation, the amplified signal 120 is received at beam displacer 2310, which

spatially separates beam 120 into two polarized beams 2315a and 2315b. The

polarization of beam 2315b is rotated by ninety degrees by halfwave plate

15   2311. Beam 2315b propagates through rhomboid 2320, polarization rotator

2321, rhomboid 2325, crystal set 2330, and PBS 2335. Beam 2315a propagates

through rhomboid 2320 and polarization rotator 2321. The polarization of

beam 2315a is rotated by ninety degrees first by halfwave plate 2343 and then,

after reflection at surfaces 2355a and 2355b of rhomboid 2325, again by

20   halfwave plate 2346 such that the polarization of beam 2315a is the same as

that of beam 2315b. From point 2355b, polarized beam 2315a propagates

along path 2323a.

Beams 2315a-b are then received by reflective element 2340. The beam 2315a

is received at a point 2340a while beam 2315b is received at a point 2340b.

Element 2340 reflects the beam 2315b from point 2340b to point 2340a. At

point 2340a, beam 2315b is reflected along path 2323a through halfwave plate

2346 and then to point 2355b. At point 2355b, polarized beam 2315b is

reflected to point 2355a, and at point 2355a, beam 2315b is reflected through

polarization rotator 2321 to rhomboid 2320 at point 2345b. Beam 2315b is

rotated ninety degrees by polarization rotator 2321. The rhomboid 2320

reflects polarized beam 2315b from point 2345a to point 2365a. At point

2365a, polarized beam 2315b is reflected through halfwave plate 2317 to beam

displacer 2314.

Element 2340 reflects beam 2315a from point 2340a to point 2340b. At point

2340b, beam 2315a is reflected along path 2323b through PBS 2335, crystal set

2330, rhomboid 2325 and polarization rotator 2321 to point 2345b. Beam

2315a is rotated ninety degrees by polarization rotator 2321. At point 2345b,

beam 2315a is reflected to point 2365b. At point 2365b, beam 2315a is

reflected through halfwave plates 2317 and 2316 and to beam displacer 2314.

Beam displacer 2314 receives polarized beams 2315a-b and combines them

into an equalized signal 128.

Although beams 2315a-b are depicted side-by-side for illustrative purposes, in

practice, the beams 2315a-b are propagated along identical or nearly identical,

spatial paths, but in opposite directions. Guiding the polarized beams 2315a-b

along the same spatial path minimizes the effect of the varying optical

5   properties of components, with respect to spatial location, and thereby improves

the performance of the optical tilter 2300 and the quality of the equalized signal

128.

Referring now to **FIGURE 19**, there is illustrated a block diagram of an

exemplary optical tilter 2400 in accordance with a third embodiment. The

10   optical tilter 2400 includes beam displacer 2405 and beam displacer 2430. A

rhomboid prism 2409 is positioned adjacent to both beam displacer 2405 and

beam displacer 2430. The rhomboid prism 2409 preferably includes a first

reflective surface 2409a, a PBS surface 2409b, and a second reflective surface

2409c. Adjacent to the rhomboid prism 2409 is a polarization rotator 2415b,

15   followed by PBS 2420, crystal set 2425, and PBS 2429. These elements are all

placed along path segment 2413b. Adjacent to the rhomboid prism 2409 is

polarization rotator 2415a. Polarization rotator 2415a is positioned along path

segment 2413a. The path segments 2413a-b are both terminated at the

reflective element 2435 at points 2422a-b, respectively.

20   In operation, the optical tilter 2400 receives amplified signal 120 at beam

displacer 2405. Beam displacer 2405 spatially separates amplified signal 120,

resulting in beams 2410a, and 2410b. Polarized beams 2410a and 2410b are guided to the PBS surface 2409b of redirecting element 2409. PBS surface 2409b reflects beam 2410a and passes beam 2410b. Beam 2410a is reflected from PBS 2409b and received by the second reflective surface 2409c, which

5   reflects beam 2410a along path 2413a through polarization rotator 2415a to reflective element 2435. Beam 2410a is rotated twice, first by polarization rotator 2415a and then by 2415b. The net effect of these rotations is zero degrees, but the rotation allows the beam to be properly oriented for the polarization-based elements in those path segments.

10   Beam 2410b is guided along path 2413b through polarization rotator 2415b, PBS 2420, crystal set 2425, and PBS 2429 to reflective element 2435. Polarization rotator 2415b and 2415a do not affect the polarization of beam 2410b as it passes through them, because beam 2410b passes through these polarization rotators in the reverse direction. The crystal set 2425/PBS 2429

15   pair forms a harmonic filter 605 for beams 2410a-b.

The reflective element 2435 receives beam 2410a at point 2422a and beam 2410b at point 2422b. Beam 2410a is directed to point 2422b, while beam 2410b is directed to point 2422a. At point 2422b, reflective element 2435 directs polarized beam 2410a along spatial path 2413b through PBS 2429,

20   crystal set 2425, PBS 2420 and polarization rotator 2415b to element 2409. Crystal set 2425 and PBS 2420 form a Fourier harmonic filter for beam 2410a.

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At point 2422a, reflective element 2435 reflects polarized beam 2410b along

spatial path 2413a through polarization rotator 2415a to second reflective

surface 2409c. Surface 2409c reflects beam 2410b to PBS surface 2409b. The

PBS surface 2409b directs beams 2410a and 2410b through first reflective

5   surface 2409a, wherein beam 2410a is received at point 2431a and beam 2410b

is received at point 2431b. First reflective surface 2409a reflects beams 2410a

and 2410b through halfwave plate 2417 to beam displacer 2430. Beam

displacer 2430 combines beam 2410a and beam 2410b, thereby resulting in

equalized signal 128.

10   Guiding polarized beams 2410a-b to traverse the same spatial locations within

the components, e.g., PBS 2420, crystal set 2425, and PBS 2429, causes the

effects of the differing optical properties due to imperfections in the materials

and fabrication to be minimized. Accordingly, the performance of the optical

tilter 2400 and the quality of the equalized signal 128 are improved.

15   Although preferred embodiments are illustrated in the accompanying drawings

and described in the foregoing detailed description, it should be understood that

numerous other embodiments, rearrangements, modifications and substitutions

are possible without departing from the spirit of the inventions as set forth and

defined by the following claims. For example, the above preferred

20   embodiments describe the controllable filtering of incoming optical signals in

order to equalize those signals or otherwise impart certain output power

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spectrums from the described embodiment equalizers. It is also possible to amplify certain portions of the incoming signal to achieve a flat output power spectrum or more complexly shaped output power spectra. Thus, the component assembly could also include optical amplifier elements instead of or

5   in addition to optical filters. The component assembly could in that instance impart a wavelength-dependent gain transfer function to the incoming signal, instead of a wavelength-dependent attenuation transfer function, or the component assembly could impart some mixture of the two. An optical "element" is a general term for an optical component or sub-component, and

10   possible specific examples of such elements or components include crystals, liquid crystals, beam deflectors, polarizers, halfwave plates, PBSs, Faraday rotators, TIR elements, and birefringent elements. Filter stages may be comprised of crystal sets and/or crystal sets matched with one or more liquid crystals and/or polarizers. General terms such as "optical element" and other

15   general terms set forth in the claims therefore should be given open meanings to accordingly cover specific embodiments falling within the general meaning of those general terms.